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Improving Relocatable Classroom HVAC for Improved IEQ and Energy Efficiency

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ABSTRACT

Relocatable classrooms (RCs) in California (CA) alone house about 2 million students in more than 80,000 structures. These buildings are typically under-ventilated, often due to low HVAC utilization because of excessive HVAC acoustic noise, and because when automatically operated they only ventilate during thermal conditioning. It can be predicted that such conditions affect the quality education and student health. These systems are also energy inefficient and peak-load demanding. With a manufacturer of wall-mounted HVAC systems, we are developing a new system addressing these problems. Design goals include a ≥30% increase the seasonal energy efficiency ratio (SEER) over the current SEER 10 system, noise reduction ≤45 dB(A), continuous ventilation meeting CA State code requirements (e.g. ASHRAE 62.1 ventilation standard of 7 l s^{-1} per occupant and a pre-occupancy air purge). The prototype was operated in an RC test-bed to characterize its performance from the standpoint of ventilation, and thermal control, acoustical noise, and energy consumption. Ten of the new HVAC systems are also being monitored for one year in matched pairs with the current standard HVAC systems after being installed in identical occupied RCs in four schools in Northern and Southern CA. Continuous measurements include indoor and outdoor carbon dioxide, temperature, relative humidity, and HVAC power consumption. Additionally, acoustical noise levels; thermal comfort; and concentrations of volatile organic compounds, formaldehyde and acetaldehyde, and ozone will be measured on a regular schedule throughout the study year. Daily classroom occupancy rates will be collected from the class records. The potential IEQ and energy savings benefits of the system will be presented from preliminary data collected in the field.

INDEX TERMS

Acoustics, Ventilation, Field study, Thermal conditioning

INTRODUCTION

Indoor environmental quality (IEQ) in schools is a public health issue that has begun to receive considerable attention. As energy costs continue to rise, the expense of ventilating and conditioning classroom spaces increases the strain on public school districts already suffering from continued budgetary crises. The design and operation of heating, ventilating, and air conditioning (HVAC) equipment used by these institutions is central to both the IEQ and energy issues that they face. Ongoing research at Lawrence Berkeley National Laboratory (LBNL) has focused on addressing the tradeoffs between the need to save energy and provide adequate ventilation in buildings, with the purpose of dispelling the common thinking that these factors are mutually exclusive.

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The study of relocatable classrooms (RCs) is relevant to current building stock issues and serves as an excellent focus for addressing IEQ problems in schools. An estimated 85,000 RCs are currently in place in California schools, housing an estimated 2 million students during the school day. The penetration of RCs into the CA school housing stock is increasing at thousands per year (CARB/CDHS 2003; EdSource, 1998; Sarich, 2001).

Evidence, both anecdotal and data from survey, suggests that HVAC systems in RCs are not operated effectively, with mechanical ventilation frequently underutilized for a number of reasons, including inadequate training in HVAC operation; system noise; energy saving measures; and inadequate control systems, maintenance and installation practices (CARB/CDHS 2003; Shendell 2003). IAQ and physical environmental stresses can adversely impact the health of students and teachers. The need for an improved classroom ventilation system is based, in part, on the considerable evidence, summarized in Daisey et al. (2003), indicating that ventilation rates in CRs often do not meet the current ASHRAE minimum rate of 7 $l\ s^{-1}$ (15 CFM) per occupant (ASHRAE 2004). In a recent survey of California RCs carbon dioxide (CO_2) concentrations exceeded 1000 ppm in about 40% of RCs and concentrations exceeded 2000 ppm in approximately 10% of CRs (CARB-DHS 2003).

A number of studies (e.g., Seppanen et al. 1999, Wargocki et al. 2002; Erdmann and Apte 2004) have investigated the relationship of ventilation rates to health outcomes (sick building syndrome symptoms, respiratory illnesses), absence rates, and perceived air quality; however, most studies have been performed in office buildings. Some studies have used indoor CO_2 concentrations as a surrogate for ventilation rate per occupant. A large majority of these studies have found a worsening of some health, absence, or perceived air quality outcomes at lower ventilation rates or higher CO_2 concentrations.

Anecdotally, we know ventilation rates in RCs are often low because teachers frequently operate their HVAC systems in the mode where the ventilation shuts off except when heating or cooling is required. We also know anecdotally that teachers operate the HVAC system this way to avoid HVAC system-related noise. These reports are supported by the findings from the CARB-DHS survey where teachers in 60% of RCs reported that they sometimes turned off HVAC systems to reduce noise levels (CARB-CDHS 2003). This indicates the importance of reducing HVAC noise in the development of improved classroom HVAC systems. From the energy standpoint, the existing HVAC systems' efficiency may not meet their rated values: four 10 SEER Bard systems studied in the field over a year were found to have effective energy efficiency ratio (EER) of about 7 (Rainer et al., 2003).

When we consider these factors together – the important effects of ventilation on people, the energy used for ventilation, and the evidence of ventilation deficiencies in classrooms, it is very clear that we need to develop and promote use of highly energy efficient systems for providing classroom ventilation. In this paper we discuss the development and testing of an improved wall-mount HVAC system for RCs that addresses energy efficiency, ventilation and ventilation controls, and acoustics in a package suitable for new construction as well as replacement/retrofit applications.

RESEARCH METHODS

Working in collaboration with Bard Manufacturing Company and Geary Pacific Supply (Bard/GP), major manufacturer and distributors of the wall-mounted HVAC systems predominantly installed on RCs, we have developed a prototype improved heat pump air conditioner (IHPAC). LBNL and Bard have collectively engineered a system to meet the following goals: 1) improve the energy efficiency to at rated Seasonal Energy Efficiency Ratio (SEER) of 13; 2) improve ventilation controls by separating ventilation from thermal conditioning and providing for a CA code required pre-occupancy ventilation purge of 3 air exchanges (CA Title 24 2001, CCR 1995); 3) lower noise levels under standard test conditions to, or below 45 dB(A) under the loudest operation mode; 4) design for a simple replacement procedure for existing systems being replaced or upgraded.

Laboratory Study

An RC from a lease fleet was installed at LBNL and instrumented with continuous energy and ventilation monitoring equipment (Table 1) at the beginning of September 2004. The RC was furnished with desks, and occupancy was simulated with thirty 67W incandescent lamps placed in a standard seating pattern at desks. Pure CO_2 gas was injected at the location of each student lamp, at a rate of 88 cc min^{-1} to simulate occupant respiration. The lamps and CO_2 injection were tied to a timer that followed a typical school bell schedule. The RC, a standard 7.3 x 12.2 m (24'x40') structure was atypical in that it was assembled from two opposite module halves each equipped with an RC HVAC system. This enabled the installation of a new IHPAC on one side while leaving a SEER 10 system on the other, allowing for direct performance comparisons between the two systems while using the same building. A new supply plenum is used with the IHPAC, allowing for three supply ducts rather than the two often used in RCs. Three ceiling supply registers replace the two existing. Both HVAC systems were adjusted to provide 230 l s^{-1} (480 CFM). Energy and ventilation measurements were conducted continuously during many days of operation using the SEER 10 system followed by several weeks using the IHPAC. The systems were each operated under both heating and cooling conditions depending on changing weather during the fall of 2004.

Relative energy savings of the IHPAC relative to the 10 SEER are calculated in two steps using the data collected in the laboratory. First, daily net energy loads from operation of both HVAC systems are calculated considering thermal changes due to building shell conduction and ventilation, internal heat loads (lights and simulated occupants, etc.), measured solar irradiance. This is divided by the total HVAC energy consumed for that day to create an approximate energy efficiency ratio (AEER). Due to many unmeasured assumptions (i.e., true overall shell conductance value) this ratio cannot be considered exact. However, those parameters that are estimated are constants and can be considered unchanging during daily operation using either HVAC system. Thus in the second step we divide the average daily AEER from the 10 SEER system days by that of the IHPAC. This second ratio is more accurate because many of the assumptions cancel out, and can be considered a reasonable estimate of improved energy efficiency by the IHPAC.

Indoor noise levels are assessed according to an Acoustical Society of America (ASA) guideline that indoor noise criteria (NC) levels should not exceed NC-25 to NC-30. The ASA also provide a guideline of 35 dB(A) (ASA 2002).

Field Study

One school district each in northern and southern CA were recruited to participate in this study through contacts made through Bard/GP. Two schools in each district were selected. In December 2004, five IHPAC systems and associated ducting and hardware were retrofitted into RCs in each district. Each of the ten RCs with the new IHPAC systems were sited next to one of six control RC equipped with an existing 10 SEER system. Thus, four 2:1 and two 1:1 matched sets of RCs were created for a total of sixteen study RCs. All of the RCs under study in each district were from the same manufacturer and each matched set of RCs consisted of RCs of the same age.

Table 1. Laboratory (L) and Field (F) study instrumentation

Parameters	Site	Instrument	Calibration method
Air temp.	L/F	Onset Instrument, HOBO-Pro	NIST traceable
RH	L/F	Onset Instrument HOBO® Temp., RH	RH over salt solutions
CO_2	L/F	California Analytical Instruments, infrared, ZPF-9, 0-3000 ppm range	Primary standard cal. Gases
Air temp., RH, CO_2	F	PureChoice Nose (www.purechoice.com)	NIST-traceable calibrations
Ventilation rate	L/F	SF_6 (unoccupied RC only) and CO_2 tracer gas step up and decay	Primary standard cal. Gases
Particle number/size	F	Met One 237B optical particle counter	Factory calibration
Aldehydes	F	Treated silica-gel cartridges (Waters WAT047205) ASTM meth. D-5197-97.	Spiked with standard aldehydes
VOCs	F	Modified Tenax-TA™ sorbent tubes (CP-16251; Varian Inc.) USEPA Method TO-1	Spiked with standard VOCs
Ozone	F	Passive samplers (Ogawa 3300) analysis by IML Inc., Sheridan WY.	Nitrate standards used to calibrate IC.
Sound levels	L/F	6Hz to 20 kHz spectrum Bruel and Kjaer model 2260	Factory calibration
Power	L/F	WattNode™ true RMS power (Continental Control Systems, Boulder CO)	Factory Calibration
Thermal Comfort	F	LBNL Thermal Comfort Cart. ASHRAE Standard 55-2004	Factory Cal. checks NIST traceable methods

Each school was equipped with and i.Lon 100 LonWorks network server donated by Echelon Corporation (www.echelon.com San Jose, CA). This server was connected via twisted pair data cable to the indoor and outdoor sensors to measure temperature, relative humidity (RH), CO_2, and HVAC power and status monitoring instruments and controls. The i.Lon 100 communicates with and stores data from all of these instruments at a rate of once per minute. This system is connected via the internet to a server at LBNL that retrieves the data from the i.Lon data-logs once per hour and stores them in a relational database. Data have been collected continuously since early January 2005 from all sixteen RCs. Aggregated daily class occupancy and absence data for each RC are collected from the school offices weekly. Scheduled field visits to the RCs will occur, once each season, to acquire IEQ data including concentrations of VOCs and aldehydes, ozone, particles (6 size bins from 0.3 to 10 µm), acoustical noise data, thermal comfort, and ventilation rates.

Relative energy efficiency of the two HVAC systems under real operation can be estimated statistically in the field study using regression techniques that include ambient temperature and RH. A confounding issue is that the HVAC usage patterns between the IHPAC and control systems will be different due to differing thermostat control algorithms in the IHPAC and more importantly due to the fact that teachers often do not turn on their 10 SEER units because of the noise problem. Thus, energy data will be scrutinized and time periods with more extreme heating or cooling demands when both systems are on will be used for the statistical comparison.

RESULTS

Laboratory

Efficiency testing of the IHPAC at the Bard factory (ARI REF) yielded a rating of 13.5 SEER. The first prototype IHPAC was installed, replacing a 10 SEER unit, at the LBNL RC test bed in early September 2004. Installation on the RC was a simple bolt on procedure and no problems were encountered during the retrofit.

Preliminary energy analysis results from 10 SEER and IHPAC using a sparse amount of cooling data indicate that the IHPAC uses about 56%±15% of the energy of the 10 SEER. The measured highest output (fan and highest compressor modes) NC levels and LAeq (A-weighed sound exposure) for the 10 SEER and IHPAC systems were NC-45/55.2 dB(A) and NC-25/43.0 dB(A), respectively. Note that the IHPAC has two compressor speeds and that measured NC/LAeq at normal speed is NC-25/40.3 dB(A). Ventilation data from both the SF_6 and CO_2 tracer measurements were very consistent over 25 days of measurements with average outdoor air flow rates of 235±14 and 230±40 $l\ s^{-1}$ (500±30 and 490±80 CFM), respectively. The IHVAC controls successfully separated ventilation and thermal conditioning functions, triggering ventilation on occupancy and for the pre-occupancy purge. A technical problem related to thermal conditioning during setback periods was not fully solved at the end of the laboratory data collection period.

Field Study

As of this writing, data collection in all 16 RCs has been operating continuously for over five weeks. Of the ten IHPAC units installed, only minor equipment problems have occurred. Preliminary school day indoor CO_2 concentration data from the IHPAC RCs are consistently below 1000 ppm while the control RCs often peak above 2000 ppm. The IHPAC RCs have been provided with continuous outside air while the control RCs have not, due to lack of operation of their HVAC systems. Although the setback temperature control issue discussed above has persisted, a technical solution soon be in place.

DISCUSSION

Analyses of data from this project are just beginning. However, the preliminary data from the laboratory study indicate that the IHPAC is a distinctly quieter system. The IHPAC produces less than half the sound power of the 10 SEER unit. The laboratory results suggest that the IHPAC will meet the ASA NC guidelines but not the 35 dB(A) levels during times when the compressor is running. The 10 SEER unit sound levels converted to LAeq were 53.5 dB(A) during fan only operation.

Bard's in-house IHPAC energy rating of SEER 13.5 is in good agreement with the preliminary energy savings comparison of 56% relative to the 10 SEER Bards published effective EER of 7. The IHPAC ventilation systems and controls work as designed, and the system can be installed as a bolt-on replacement to existing units. The setback temperature control issue is the only technical problem that still must be resolved.

CONCLUSION AND IMPLICATIONS

The IHPAC system has been tested in the laboratory, and lab analyses and field testing are in progress. Preliminary results suggest that the system meets and exceeds initial design goals for energy efficiency, ventilation, acoustics, and replacement compatibility with existing systems. Efforts to stimulate the transfer of this technology to the market will lead to improvements of IEQ in RCs and improving their energy efficiency while meeting state code requirements.

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